

CAN GALACTIC COSMIC RAYS ACCOUNT FOR SOLAR  ${}^6\text{Li}$   
WITHOUT OVERPRODUCING GAMMA RAYS?

TIJANA PRODANOVIĆ AND BRIAN D. FIELDS

Center for Theoretical Astrophysics, Department of Astronomy, University of Illinois, Urbana, IL 61801

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## ABSTRACT

Cosmic-ray interactions with interstellar gas produces both  ${}^6\text{Li}$ , which accumulates in the interstellar medium (ISM), and  $\pi^0$  mesons, which decay to gamma-rays which propagate throughout the cosmos. Local  ${}^6\text{Li}$  abundances and extragalactic gamma-rays thus have a common origin which tightly links them. We exploit this connection to use gamma-ray observations to infer the contribution to  ${}^6\text{Li}$  nucleosynthesis by standard Galactic cosmic-ray (GCR) interactions with the ISM. Our calculation uses a carefully propagated cosmic-ray spectrum and accounts for  ${}^6\text{Li}$  production from both fusion reactions ( $\alpha\alpha \rightarrow {}^6\text{Li}$ ) as well as from spallation channels ( $p, \alpha + \text{CNO} \rightarrow {}^6\text{Li}$ ). We find that although extreme assumptions yield a consistent picture, more realistic ones indicate that solar  ${}^6\text{Li}$  cannot be produced by standard GCRs alone without overproducing the hadronic gamma rays. Implications for the primordial  ${}^6\text{Li}$  production by decaying dark matter and cosmic rays from cosmological structure formation are discussed. Upcoming gamma-ray observations by *GLAST* will be crucial for determining the resolution of this problem.

*Subject headings:* cosmic rays – gamma rays: theory – nuclear reactions, nucleosynthesis, abundances

## 1. INTRODUCTION

Cosmic-ray nucleosynthesis is the only known Galactic source of the  ${}^6\text{Li}$  (Vangioni-Flam et al. 1999; Fields & Olive 1999). Thus, it is a standard belief that the observed solar abundance of  ${}^6\text{Li}$  was produced by Galactic cosmic-ray (GCR) interactions with the interstellar medium (ISM), where  $\alpha\alpha \rightarrow {}^6\text{Li}$  is the dominant channel (Steigman & Walker 1992; Montmerle 1977). However, hadronic CRs also produce gamma rays, and thus GCR interactions in normal galaxies are guaranteed to contribute (Pavlidou & Fields 2002) to the observed extragalactic gamma-ray background (hereafter EGRB; Strong et al. 2004). Moreover, since they both originate from CR interactions,  ${}^6\text{Li}$  and hadronic gamma-rays are tightly related.

Fields & Prodanović (2005) established a simple and model-independent connection between lithium and “pionic”  $\gamma$ -ray production ( $pp \rightarrow \pi^0 \rightarrow \gamma\gamma$ ) by a given cosmic-ray population. Using this tool with simplifying assumptions gave the alarming result that the solar  ${}^6\text{Li}$  abundance, if produced entirely by GCRs, demands a pionic  $\gamma$ -ray intensity exceeding the *entire* observed EGRB (Fields & Prodanović 2005). Given the current interest in  ${}^6\text{Li}$ , this result thus deserves a thorough investigation.

In this paper we revisit the problem of Li- $\gamma$ -ray consistency with a more precise and realistic calculation. We now employ a carefully propagated CR spectrum, as opposed to the standard single-power law spectrum adopted in Fields & Prodanović (2005). Moreover, instead of using a convenient fit for the pionic  $\gamma$ -ray spectrum (Pfrommer & Enßlin 2004) we now calculate it self-consistently from our CR spectrum. We also estimate the spallation  $p, \alpha + \text{CNO} \rightarrow {}^6\text{Li}$  contribution to the solar  ${}^6\text{Li}$  abundance. These effects slightly reduce but do not eliminate the discrepancy. Moreover, the only remaining effect we expect to be important— ${}^6\text{Li}$  destruction as it is processed through stars—makes the problem more severe. The net effect is that in a realistic calculation, the

observed EGRB allows for only  $\approx 60\%$   ${}^6\text{Li}_\odot$  to be produced by standard GCRs. Only a conspiracy of extreme assumptions gives GCR production of the solar  ${}^6\text{Li}$  that does not at the same time saturate the observed EGRB.

Our result represents a strong hint for the need of a new  ${}^6\text{Li}$  source. Recent suggestions such as dark matter and low-energy cosmic rays are discussed in §6. Upcoming gamma-ray observations by *GLAST* (Gehrels & Michelson 1999) will better constrain (or determine!) the pionic  $\gamma$ -ray fraction of the EGRB and will thus be the key in determining the severity of this problem.

## 2. LITHIUM-GAMMA-RAY CONNECTION

In Fields & Prodanović (2005) we formally demonstrated and quantified the tight connection between CR lithium synthesis and hadronic  $\gamma$ -ray production. We showed that both observables are a measure of the time-integrated CR flux (fluence  $F$ ). Specifically, the ratio of the “pionic”  $\gamma$ -ray intensity  $I_{\gamma\pi}$  (integrated over the entire energy spectrum) and  ${}^6\text{Li}$  abundance (baryon or mole fraction  ${}^6\text{Li} \equiv Y_6 \equiv n_6/n_{\text{baryon}}$ ) produced in fusion reactions with the ISM can be expressed essentially as the ratio of their reaction rates

$$\frac{I_{\gamma\pi}(E > 0, t)}{{}^6\text{Li}(\vec{x}, t)} = \frac{n_b c}{4\pi y_{\alpha, \text{cr}} y_{\alpha, \text{ism}}} \frac{\sigma_\gamma}{\sigma_6} \frac{F_{\text{avg}}(t)}{F_{\text{MW}}(t)} \quad (1)$$

This factorizes into a product of nuclear, cosmological, and cosmic-ray parameters, and a “Copernican” factor  $F_{\text{avg}}/F_{\text{MW}}$ . Cosmology enters via the comoving baryon number density  $n_b = 2.52 \times 10^{-7} \text{ cm}^{-3}$ . The cosmic-ray and ISM helium abundances are taken to be  $y_\alpha^{\text{cr}} = y_\alpha^{\text{ism}} = 0.1$  ( $y_i \equiv n_i/n_H$ ). The flux-averaged pionic  $\gamma$ -ray production cross-section is  $\sigma_\gamma \equiv 2\xi_\alpha \zeta_\pi \sigma_{\pi^0}$  where the factor of 2 counts the number of photons per pion decay,  $\sigma_{\pi^0}$  is the cross section,  $\zeta_\pi$  is the pion multiplicity, and the factor  $\xi_\alpha = 1.45$  accounts for  $p\alpha$  and  $\alpha\alpha$  reactions (Dermer 1986). For  $\sigma_6$  we have used a recent result of

Mercer et al. (2001), which for  ${}^6\text{Li}$  differs significantly from the old values. The use of the new cross sections results in a lower  ${}^6\text{Li}$  production.

The ratio  $F_{\text{avg}}/F_{\text{MW}}$  is the ratio of the line-of-sight baryon-averaged fluence to the local fluence; this ‘‘Copernican ratio’’ compares the cumulative cosmic-ray activity of our Galaxy to that of an average star-forming galaxy. Following our previous work we will initially take this factor be  $\approx 1$ , i.e. that the Milky Way CR flux through out the history can be approximated with the cosmic mean. We will then examine the consequences that this ratio differs significantly from unity.

### 3. COSMIC-RAY SPECTRUM

In eq. (1), the Li- $\gamma$ -ray proportionality depends on the ratio of the mean cross sections  $\sigma_\gamma/\sigma_6$ . These must be properly averaged over the GCR energy spectrum. In Fields & Prodanović (2005) we have adopted a standard propagated cosmic-ray spectrum which is a single power-law in total energy with a spectral index  $\alpha = 2.75$  over the entire relevant energy range. While this is a commonly-used rough approximation to the GCR spectrum, it becomes inaccurate at energies  $\lesssim 1$  GeV, where ionization energy losses dominate over escape losses. Because  $\alpha\alpha \rightarrow {}^6\text{Li}$  threshold energy is at  $\sim 10$  MeV/nucleon, while  $\text{pp} \rightarrow \pi^0$  threshold is at  $\sim 280$  MeV, the Li- $\gamma$  connection is particularly sensitive to GCR behavior at very low energies. Thus in this paper we refine on the analysis presented in Fields & Prodanović (2005) by calculating and implementing a carefully propagated CR spectrum for a leaky box model (Meneguzzi et al. 1971).

The resulting CR spectrum calculated using the standard leaky box model, assuming a standard source spectrum that is a power-law in momentum (Gaisser 1990, e.g.). This gives a CR flux  $\sim 4$  times higher around  $\alpha\alpha \rightarrow {}^6\text{Li}$  threshold, compared to the one used in Fields & Prodanović (2005) where a single power-law spectrum was assumed, while for energies  $\gtrsim 100$  MeV a single-power law spectrum is a good approximation.

### 4. PIONIC GAMMA-RAY SPECTRUM

Pfrommer & Enßlin (2004) provide a useful parametrization of the pionic  $\gamma$ -ray spectrum used in Fields & Prodanović (2005). However, here we numerically calculate the pionic  $\gamma$ -ray spectrum in full detail, by adopting the isobar+scaling model as given in Dermer (1986); the pionic spectrum we adopt uses the same cosmic-ray spectrum as the  ${}^6\text{Li}$  production, and thus is self-consistent.

In order to calculate  $I_{\gamma\pi}$  one needs to know the history of the CR sources and the targets. Both histories come from the cosmic star-formation rate. As described in detail in Fields & Prodanović (2005) we can obtain the GCR pionic  $\gamma$ -ray spectrum integrated over the history of the sources (equation 26 of Fields & Prodanović 2005, same parameter values used). The cosmic star-formation rate alone fixes the *shape* of the pionic EGRB, but requires a normalization that physically connects the star formation rate to the cosmic-ray flux, and which normalizes the present gas fraction in a typical galaxy. In order to place an *upper limit* to the pionic EGRB, we allow this normalization to vary freely to maximize the pionic  $\gamma$ -ray flux consistent with present EGRB observations

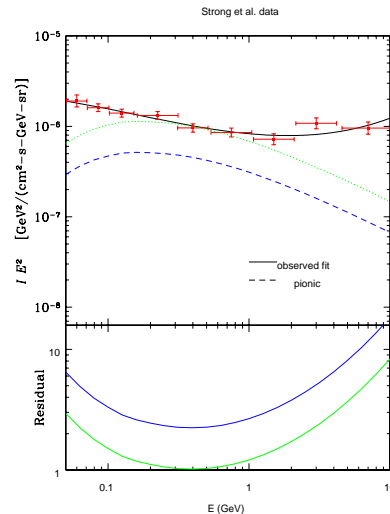


FIG. 1.— In the upper panel of this figure, we plot the pionic spectrum (dotted green line - maximized, dashed blue line - normalized to the Milky Way), compared to the observed EGRB spectrum (solid line, fit to data); we use the Strong et al. (2004) data points, which are given in red crosses. The bottom panel represents the residual function, that is,  $\log[(IE^2)_{\text{obs}}/(IE^2)_\pi] = \log(I_{\text{obs}}/I_\pi)$ .

(Fields & Prodanović 2005; Prodanović & Fields 2004). This is presented in Fig. 1 as a dotted green line. The observed EGRB spectrum is that of Strong et al. (2004) and is plotted as red data points, with a black solid line fit (Fields & Prodanović 2005). Finally, we find maximal pionic  $\gamma$ -ray fraction to be 58% of the total observed EGRB.

More realistically, we can use the Milky Way to determine both the scaling between the star formation rate and the cosmic-ray flux, and the present-day gas fraction. We do this following Pavlidou & Fields (2002), using a present gas content of the Milky Way  $M_{\text{gas,MW}} \approx 10^{10} M_\odot$ , and a star formation rate  $3.2 M_\odot/\text{yr}$ . The resulting  $\gamma$ -ray spectrum is presented in Fig. 1 as a blue dashed line. This corresponds to the pionic  $\gamma$ -ray contribution expected from the normal galaxies. In addition to this guaranteed component to the EGRB, unresolved blazars will also contribute significantly (Stecker & Salamon 1996; Pavlidou & Fields 2002), presumably comprising much or all of the remaining signal.

Having determined an upper limit and a more realistic estimate to  $I_{\gamma\pi}$  one can find the corresponding Li abundance, via eq. (1). This is our main goal, to which we now turn.

### 5. UPPER LIMITS ON AND ESTIMATES OF GCR-PRODUCED ${}^6\text{Li}$

In this section we calculate limits to and estimates of the  ${}^6\text{Li}$  produced by GCRs that are allowed by preset EGRB data. We present our results in steps of increasing realism. For now we retain the Copernican assumption that the Milky Way cosmic-ray fluence is typical of star-forming galaxies ( $F_{\text{MW}}/F_{\text{MW}} = 1$ ); we will revisit this assumption in the final section.

1. By combining (1) with the *maximal* pionic  $\gamma$ -ray

fraction and procedure described in Fields & Prodanović (2005), we find the fraction of  ${}^6\text{Li}$  abundance produced in  $\alpha\alpha \rightarrow {}^6\text{Li}$  reaction to be  ${}^6\text{Li}_{\alpha\alpha} = 0.61 {}^6\text{Li}_{\odot}$  ( $({}^6\text{Li}/\text{H})_{\odot} = 1.53 \times 10^{-10}$ ; Anders & Grevesse 1989). This corresponds to an extreme upper limit for all  ${}^6\text{Li}$  produced by the GCR  $\alpha\alpha$  reaction.

2. Though the  $\alpha\alpha$  reaction with the ISM is the dominant channel for  ${}^6\text{Li}$  production, a non-negligible contribution, especially at higher metallicity, comes from the spallation reactions  $p, \alpha + \text{CNO} \rightarrow {}^6\text{Li}$  (both forward and inverse kinematics, that is fast heavy nuclei, are included). If the fusion and CNO reaction rates were to be equal the required oxygen abundance should be  $(\text{O}/\text{H})_{\text{eq}} = 0.51 (\text{O}/\text{H})_{\odot}$ . This now sets the normalization and allows us to calculate the total  ${}^6\text{Li}$  abundance produced from all channels under the extreme assumption that the ISM was at *solar metallicity* over the Galactic history. We find that  ${}^6\text{Li}_{\text{GCR}} = 1.79 {}^6\text{Li}_{\odot}$ , which now represents the extreme upper limit for *all*  ${}^6\text{Li}$  produced by GCRs.

3. Because the cosmic-ray CNO abundance is a direct function of the Galactic supernova rate, a precise calculation introduces a factor of 1/2, that is, instead of assuming solar metallicity through out history one should use an average value of  $(\text{O}/\text{H})_{\text{eq}} = 0.5 (\text{O}/\text{H})_{\odot}$ . This results in the total allowed GCR-produced  ${}^6\text{Li}$  abundance of  ${}^6\text{Li}_{\text{GCR}} = 1.20 {}^6\text{Li}_{\odot}$ , which is still consistent with the standard picture.

4. So far we have been taking the maximal (Fig. 1, dotted green line) pionic  $\gamma$ -ray fraction as allowed by the present EGRB data<sup>1</sup>, where we have (without justification) ignored the normalization and just used the shape of our spectrum. However, it is unrealistic to assume that the entire emission is due to GCRs. Indeed, independent of the details of our galactic  $\gamma$ -ray estimate, it is clear that the EGRB must contain a large and perhaps dominant contribution from unresolved AGNs (blazars) and so the galactic signal must leave room for this and cannot saturate the observed level. An estimate of the normalized GCR pionic  $\gamma$ -ray component of the EGRB (Fig. 1, dashed blue line) yields a spectrum that is a factor of 2.1 lower than the maximized value. Thus, in this most honest case, we find  ${}^6\text{Li}_{\text{GCR}} = 0.57 {}^6\text{Li}_{\odot}$  which now falls short by about a factor of 2 from a standard picture of cosmic-ray  ${}^6\text{Li}$  nucleosynthesis.

5. For inverse CNO kinematics a non-negligible LiBeB production comes from two-step spallation reactions, eg.  $\text{O} + \text{H} \rightarrow {}^{11}\text{B} + \text{H} \rightarrow {}^6\text{Li}$  (Kneller et al. 2003). For example, the production rate of  ${}^6\text{Li}$  from two-step reactions of fast oxygen is  $\sim 40\%$  of single-step fast oxygen spallation reactions, for a fixed  $\Lambda = 10 \text{ g/cm}^2$  (Kneller 2006). However, when two-step inverse CNO kinematics is taken into account, the overall increase is only slight and the result now becomes

$${}^6\text{Li}_{\text{GCR}} = 0.59 {}^6\text{Li}_{\odot} \quad (2)$$

Even in the most extreme assumption that the two-step rates are equal to the single-step inverse CNO kinematic rates, the resulting  ${}^6\text{Li}$  abundance would still be only 63% of the solar.

<sup>1</sup> Determination of the EGRB relies on the subtraction of the Galactic Plane and is thus model-dependent. Although Keshet et al. (2004) report only a limit to the EGRB this would only strengthen our result.

6. Finally, one has to remember that the observed solar  ${}^6\text{Li}$  abundance is not the total lithium abundance produced, due to astration, that is, the fact that some of the gas was already processed by stars. Due to very fragile nature of this isotope,  ${}^6\text{Li}_{\odot}$  is only the lower bound on the total  ${}^6\text{Li}$  produced. For a rough estimate of the level of astration one can use deuterium. It is well established that Big Bang nucleosynthesis is the only important source of D (Epstein et al. 1976; Prodanović & Fields 2003) and that D is easily destroyed in stars due to a similarly fragile nature. Thus by comparing the solar nebula D abundance  $D_{\text{presol}} = 2.1 \times 10^{-5}$  (Geiss & Gloeckler 1998) with the abundance determined from 5 best quasar absorption systems  $D_{\text{QSO}} = 2.78 \times 10^{-5}$  (Cyburt et al. 2003), we find that roughly  $\sim 25\%$  of the gas has passed through stars. Thus  ${}^6\text{Li}_{\odot}$  is about  $\sim 75\%$  of  ${}^6\text{Li}_{\text{tot}}$ , and our calculated GCR  ${}^6\text{Li}$  now becomes  ${}^6\text{Li}_{\text{GCR}} \sim 0.45 {}^6\text{Li}_{\text{tot}}$ .

## 6. DISCUSSION

In this paper we have used the connection between  ${}^6\text{Li}$  and pionic  $\gamma$ -rays produced in CR interactions, in order to calculate the total allowed  ${}^6\text{Li}$  abundance that can be produced by GCRs. We have used a CR spectrum, carefully propagated according to the leaky-box model, while the pionic  $\gamma$ -ray spectrum was calculated based on the Dermer (1986) model. A realistic, detailed calculation that includes  ${}^6\text{Li}$  production from both fusion reaction with the ISM and spallation CNO channels (2-step inverse kinematics also included), yields a  ${}^6\text{Li}$  abundance that is only  $\approx 60\%$  of the total  ${}^6\text{Li}$  produced, if standard GCRs are the only relevant source. Correcting for astration will result in even lower  ${}^6\text{Li}_{\text{GCR}}$  abundance at the level of  $\sim 45\% {}^6\text{Li}_{\text{tot}}$ .

Our result either indicates the need for a new important source of  ${}^6\text{Li}$  beyond standard GCR nucleosynthesis, or it points to a possible failure of the usual assumption that the average interstellar GCR flux tracks the instantaneous star formation rate. We consider each possibility in turn.

Additional sources of  ${}^6\text{Li}$  are of considerable current interest, because of the recent report of a  ${}^6\text{Li}$  plateau in metal-poor halo stars (Asplund et al. 2005). As with the familiar  ${}^7\text{Li}$  Spite plateau, an analogous  ${}^6\text{Li}$  feature would suggest a pre-Galactic source of  ${}^6\text{Li}$ . And indeed, recently two very different cosmological sources of  ${}^6\text{Li}$  have been proposed: (1) production in the early universe, stimulated by supersymmetric dark matter particle decays during big bang nucleosynthesis (Dimopoulos et al. 1988; Kawasaki et al. 2005; Jedamzik et al. 2005; Ellis et al. 2005; Kusakabe et al. 2006); and (2) production during the virialization and baryonic accretion of large-scale structures, which generates cosmological shocks (Miniati et al. 2000) that can in turn accelerate a population of cosmological cosmic rays (Suzuki & Inoue 2002; Blasi 2004, but see Prantzos (2006) for constraints).

The  ${}^6\text{Li}$  plateau is  $\lesssim 10\% {}^6\text{Li}_{\odot}$ , and thus whatever its source is, it will not be able to account for the factor  $\gtrsim 2$  discrepancy between  ${}^6\text{Li}_{\odot}$  and  ${}^6\text{Li}_{\text{GCR}}$  we have found. However, the existence of the  ${}^6\text{Li}$  plateau at the 10% level of the solar abundance for metallicities  $[\text{Fe}/\text{H}] \lesssim -1$ , can be used as a constraint to any non-standard  ${}^6\text{Li}$  source that is expected to account for the potentially missing

$\approx 40\%$  of  ${}^6\text{Li}_\odot$ . Moreover,  ${}^6\text{Li}$  plateau would indicate that such a source would have to become important only at late times, and near-solar metallicities.

We note that another additional source of  ${}^6\text{Li}$  could come from a population of CRs having low energies ( $\lesssim 100$  MeV). Such particles are excluded from the solar system and hence not directly constrained observationally. A large flux of such particles, well above the extrapolated observed high-energy trends, could produce large additional amounts of  ${}^6\text{Li}$  but no pions and hence no pionic  $\gamma$ -rays. Indeed, recent observations of  $\text{H}_3^+$  in molecular clouds (McCall et al. 2003) seem to demand a large low-energy CR flux in the neighborhood of these clouds. On the other hand, low-energy CRs widespread enough to participate significantly in LiBeB nucleosynthesis on Galactic scales face strong constraints that come from energetics (Ramaty & Lingenfelter 1999) and from LiBeB abundance ratios (Vangioni-Flam et al. 1998). These limits are evaded if solar  ${}^6\text{Li}$  reflects a localized low-energy CR enhancement, either due to a hypernova-like Type Ic supernova (Fields et al. 2002; Nakamura & Shigeyama 2004), or to solar CR production in the protosolar nebula (e.g., Gounelle et al. 2006). In either case, the other  ${}^7\text{LiBeB}$  isotopes will be produced and constrain the allowable  ${}^6\text{Li}$  contribution.

In this work we have assumed that the Milky Way CR fluence can be approximated with the cosmic mean. Therefore, our result might indicate that more  ${}^6\text{Li}$  was produced than  $\gamma$ -rays would suggest, which would be the case if the Milky Way CR flux was at some time(s) a factor of  $\sim 2$  (on average) higher than the typical CR flux in a normal galaxy.

If indeed  ${}^6\text{Li}$  points to enhanced CR activity, this in turn would point to anomalies in Milky Way star formation and/or CR properties. We have assumed that the CR fluence here is typical of the mean star-forming galaxy ( $F_{\text{MW}}/F_{\text{avg}} = 1$ ). If instead our Galaxy had a

more vigorous CR history, this could account for the difference. Also, we have in our most realistic assessment used the present *local* cosmic-ray/star-formation ratio  $\Phi_{\text{MW}}/\psi_{\text{MW}}$ ; if this departs from the cosmic mean, this too could account for the  ${}^6\text{Li}$  discrepancy. Both of these solutions have implications for (and quantify) the utility of the Milky Way and Local Group as representative cosmological samples of star forming galaxies.

Upcoming gamma-ray experiments will go far to clarify the nature of Galactic and extragalactic pionic gamma-rays, and hence  ${}^6\text{Li}$  production. *GLAST* could detect the pionic  $\gamma$ -ray signature from diffuse Galactic emission as well as in the EGRB; this would remove the need to estimate these components. *GLAST* should also detect several Local Group galaxies and thus allow for new determinations of the cosmic-ray/star-formation scaling (Pavlidou & Fields 2001). Also, our calculation is hampered by lack of evidence of the “pion bump” in the Milky Way  $\gamma$ -ray spectrum. Fortunately, it was recently demonstrated that future GeV–TeV–PeV gamma-ray observations of the diffuse emission from the Galactic Plane can determine the level of pionic  $\gamma$ -ray emission in the Milky Way (Prodanovic et al. 2006).

In closing, we have underscored the increasing crucial role that  ${}^6\text{Li}$  plays in particle astrophysics and cosmology; the excess we find in solar  ${}^6\text{Li}$  has implications throughout these fields. Fortunately, upcoming measurements of  ${}^6\text{Li}$  and gamma-rays should be able to address the questions posed here.

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